NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3074

A PRELIMINARY INVESTIGATION OF THE EFFECTS OF GUSTY AIR ON HELICOPTER-BLADE BENDING MOMENTS

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SUMMARY

A preliminary investigation has been made at the Langley helicopter test tower to determine the bending moments excited on typical helicopter blades in quiet and gusty air.

The results obtained from the limited range of this investigation indicate that the effects of gusts on rotor-blade bending moments appear to be secondary when compared with the vibratory moments attributed to the unsymmetrical rotor downwash for the 26-mph wind-velocity condition tested and analyzed. It was also found that the addition of weight at the blade tips reduced the magnitude of the blade vibratory bending moments.

INTRODUCTION

The successful development of different types of helicopters for highly specialized uses is dependent to a large extent upon achieving refined aerodynamic and structural design. One of the general problems about which there is little information is the effect of gusts on rotor-blade flapwise bending moments.

Accordingly, a preliminary investigation has been completed, the primary objective of which was to determine whether rotor-blade bending moments are significantly affected by gusts and, if so, to determine the relative magnitude of these effects. The tests were made on the Langley helicopter test tower in calm air and in gusty wind conditions.

Time histories of the rotor-blade bending moments and the indicated gust conditions were obtained. Since blade vibratory bending moments, aside from gust effects, may be caused largely by the dissymmetry in rotor downwash under lifting conditions at the forward speeds encountered during these tests, tests were also made in gusty air at zero rotor lift, zero rotor angle of attack, and zero blade angle of attack to eliminate the effects of downwash. An analysis similar to that made for forward flight by the Cornell Aeronautical Laboratory, Inc. (ref. 1) was performed to explain the bending-moment data obtained. In the present investigation, a 48-point Fourier analysis of the blade bending moments was made to determine the amplitude and frequency of the first 10 harmonics. The results of the analysis are presented herein, together with a limited amount of data on the effects of tip weight on blade vibratory and mean bending moments.

DESCRIPTION OF APPARATUS

Rotor Blades

The helicopter rotor used was a conventional three-bladed rotor with flapping hinges located on the rotor shaft. A photograph of the rotor installation at the Langley helicopter test tower is shown as figure 1. The blades had a steel main spar and were covered with plywood; they had a radius of 18.62 feet, an equivalent chord of 9.9 inches, a solidity of 0.042, no twist, and an NACA 23015 airfoil section with 0.1° reflex at the trailing edge. The weight of each blade was 62.5 pounds, and the normal configuration of the blades incorporated a 1.6-pound tip weight at the 15-percent-chord station for chordwise mass balance. A limited number of tests was made with no tip weight and with a 7-pound tip weight to investigate the effect of tip weights on the blade vibratory and mean bending moments. The ratio of the 7-pound tip weight to the blade weight was 0.112. Two of the blades were instrumented with strain gages on the top and bottom of the steel main spar at the 25-, 37-, 50-, 62-, 75-, 85-, and 97-percent-spanwise-radius stations. A plan view of one of these blades is shown as figure 2.

Wind and Gust Measuring Equipment

Two instrument assemblies, each capable of detecting the wind direction and the presence of gusts, were located on poles 90° apart. The instruments were placed inside the wire protector screen in the plane of the blades, 38 feet from the center of rotation, and 2 feet from the nearest screen pole. Each instrument assembly consisted of a wind-direction indicator and two turbulence indicators; one turbulence indicator was mounted vertically and one was mounted horizontally. A picture of one assembly is shown as figure 3. The turbulence indicator consisted of a metal box which housed a strain gage, a paddle, and an oil dashpot. The movement of the paddle by an air disturbance was sensed by the strain gage which transmitted the signal to a recording oscillograph with galvanometer elements having a flat response curve up to 100 cps. The turbulence indicators showed only the frequency and relative magnitude of air disturbances for different test conditions. A measure of the horizontal-gust intensity was obtained from fluctuations in the wind-direction indicator. The wind vane mounted on top of the gust-sensing elements incorporated a slide-wire potentiometer-type transmitter. Signals from the potentiometer were transmitted to and recorded by the oscillograph. The response characteristics of the wind vane were determined by wind-tunnel tests. The natural frequency of the vane in cycles per second was 0.05 times the wind speed in feet per second, which means that it could accurately follow gusts with a duration of 0.5 or more seconds at a wind speed of 26 mph (one of the test conditions). Average wind velocity was indicated by anemometer cups mounted on a pole 40 feet high and 180 feet from the tower.

TESTS

Test Conditions

Information on blade bending moments obtained with a 1.6-pound tip weight was taken with the rotor operating in three basic conditions at a rotor angular velocity of about 4 rps. In the first of these conditions, selected as a basis to compare gust and forward-speed effects, the rotor was operated at zero thrust in calm air. The second condition, in which the rotor was operated at zero thrust in gusty 26-mph winds, was selected to bring out the effects of gusts on the blade bending moments. The third condition selected was for a rotor thrust of 2,100 pounds in gusty 26-mph winds to show the total effects of forward flight and gusts on a loaded rotor.

An investigation of the effects of tip weights on the blade bending moments was conducted in 8-mph winds at a rotor thrust of 2,100 pounds. Tests were made with tip weights of 0, 1.6, and 7.0 pounds.

Test Methods

The instrumentation discussed in reference 2 provided the following performance data: thrust, torque, cyclic and collective pitch, and shaft revolutions per second. The data were recorded on a separate oscillograph. The bending-moment signals from the strain gages located on the blade spar were fed through silver slip rings on the rotor head to a selector and control box and from there to the other oscillograph. Attempts to record all seven bending-moment traces on one record resulted in scrambling the traces to such an extent that identification of the individual traces was impossible. Accordingly, half of the information was obtained in one run, and the run was repeated to obtain the rest of the data. The time interval between the runs was about 5 minutes. Turbulence indications and wind-vane directions were transmitted directly to the selector and control box and then to the oscillograph. In order to correlate the performance and bending-moment information, a timer signal was fed into each oscillograph. For gusty wind conditions, records were taken for a period of not less than 1 minute, corresponding to about 240 rotor revolutions, so that a sufficient time history of the gusts and blade bending moments could be obtained.

Precision of the Data

The estimated accuracies of the basic quantities measured in this investigation are as follows:

Blade bending moment, percent of full-scale deflection	±3
Blade natural frequency, cps	±0.5
Thrust, lb	±15
Torque, lb-ft	±15
Pitch angle, deg	±0.2
Rotor angular velocity, rpm	±1
Average wind velocity, mph	±1
Wind direction, deg	±5

As mentioned previously, no accuracies can be quoted for the turbulence indicator since it indicated only whether the air was smooth or rough. It is believed that the overall accuracy of the performance data is 3 percent and that the accuracy of the bending-moment data is about 5 percent.

ANALYSIS

Determination of Gust Contribution

The gusts reported in this investigation are those caused by the normal turbulence of the wind. An indication of the intensity of the horizontal gusts can be obtained by measuring the angle through which the wind vane fluctuates and then multiplying the sine of this angle by the average wind speed. An explanation of the method used to determine this horizontal-gust intensity is presented in reference 3. For the test wind velocity of 26 mph, the maximum wind-direction variation was 30°, which indicated horizontal-gust velocities of the order of 15 to 20 ft/sec. These wind-vane data were used to establish the general gust levels for the test conditions. In the absence of other specific information, it is assumed that these data also indicate the general level of the vertical gusts.

Inasmuch as very gusty air occurred only at considerable wind speeds, the evaluation of the effect of the gusts requires a separation of gust effects from forward-speed effects. It is well known that large flapwise vibratory bending moments occur in rotor blades in forward flight because of unsymmetrical downwash through the rotor disk. These vibratory moments have been reported to reach a maximum at 20 to 30 mph for a helicopter of normal disk loading (2.0 to 2.5 lb/sq ft) and normal rotational tip speed (ref. 1). This is also the speed range at which the present gust tests were conducted. Higher wind velocities were not obtainable, and the turbulence level of lower wind speeds was small so that the effects of gusts were more difficult to measure.

In order to obtain an indication of the incremental bending moment due to gusts, data were obtained at zero rotor thrust (zero downwash) in both quiet and gusty air. The effects of gusts on the loaded and unloaded rotor may or may not be the same; however, an examination of the problem indicates that the gust effects as measured on the unloaded rotor can be used to judge whether the same gust effects are likely to be of more than secondary importance for the loaded-rotor case.

It is recognized that the flapwise vibratory moments recorded under various wind conditions at zero thrust may contain some small unknown increments resulting from such factors as one blade operating in the wake of a preceding blade, mechanical input from imperfections in the pitch-control assembly, inability to set exactly zero rotor thrust, and azimuthal variation in resultant velocity.

Measured Bending Moments

The frequencies at which the vibratory moments occur are very important in rotor-blade design, especially in an analysis of the expected fatigue life of rotor-blade main spars, root fittings, and hub assemblies. Reference 1 shows that the predominant blade frequencies encountered in forward flight are those corresponding to the natural frequencies of blade bending in the first, second, and third modes. Gust disturbances would be expected to have a similar effect since, presumably, the blade should act like a band-pass filter, rejecting disturbances remote from its natural frequencies but amplifying those at or near its natural frequencies. Accordingly, a 48-point harmonic analysis was made of the blade bending moments for the conditions of zero thrust and approximately zero wind velocity, zero thrust and gusty winds of 26 mph, and 2,100 pounds of rotor thrust and gusty winds of 26 mph (gusts plus unsymmetrical downwash effects). As a point of interest, an analysis was also made for the condition of 2,100 pounds of rotor thrust and relatively quiet air.

The experimental predominant blade bending frequencies were then compared with the calculated bending frequencies of the rotating blade which corresponded to the first, second, and third flapwise bending modes. The calculated frequencies were obtained by determining experimentally the static natural frequencies in these modes by means of shaker tests and then calculating the increase in natural frequencies under rotating conditions in a manner similar to that given in standard reference texts on vibrations.

The effect of blade tip weights on the mean and vibratory blade bending moments was investigated for the conditions of 0-, 1.6-, and 7.0-pound tip weights.

RESULTS AND DISCUSSION

In order to facilitate comparison of the data and to separate the effects of gusts from the effect of unsymmetrical rotor downwash associated with forward speed, the data will be discussed in three phases: (1) zero rotor thrust (no downwash) in quiet air with the wind velocity less than 3 mph, (2) zero rotor thrust in very gusty air with an average wind velocity of 26 mph, and (3) combined effects of gusts and downwash at 2,100 pounds of rotor thrust in very gusty air with an average wind velocity of 26 mph.

Zero Thrust in Quiet Air

Sample oscillograph records of the blade flapwise-bending-moment traces for the rotor operating in very quiet air at zero thrust and at approximately zero wind velocity are shown in figures 4(a) and (b). Figure 4(a) presents the records from the 25-, 50-, and 75-percent-radius stations and figure 4(b) shows the records from the 37-, 62-, 85-, and 97-percent-radius stations (where R is the blade radius).

The straight lines of the turbulence indicators show that no air disturbances were present. The bending-moment traces, however, are not straight and indicate a small amount of vibratory disturbance. As previously mentioned, various factors, such as one blade operating in the wake of the preceding blade, may excite blade vibratory moments even at zero rotor thrust and zero wind velocity.

Zero Thrust in Gusty 26-mph Winds

The increase in the blade vibratory bending moments obtained at zero rotor thrust (no downwash) due to operating in gusty air at an average wind velocity of 26 mph is shown in figures 5(a) and (b).

Air disturbances are indicated by the erratic traces of the turbulence indicators. The severe turbulent condition recorded by indicator 2 was caused by absence of oil in the indicator's dashpot damper and, therefore, this indicator should be disregarded. For most of the bending-moment traces, the amplitude is about three times as large as that shown for quiet air. There seems to be no correlation of the bending moments with the indicated gusts. This lack of correlation is not surprising in view of the fact that the blade is a vibrating system which accepts and amplifies only those disturbances near its natural frequencies. As mentioned previously, it is recognized that part of the increase in amplitude shown in figure 5 may be caused by the increase in airspeed alone. However, it is thought that gusts would have the greater effect on the blade vibratory moments by causing a change in the effective angle of attack and thereby in the lift of the blade. Although the time that the blade can be affected by a given gust is probably small, it may be sufficient to displace the blade from its normal path of rotation and, thus, to impose vibratory moments. In order to be conservative in the estimation of gust loads, the increase in blade bending moment will be considered to be wholly due to gust disturbances.

2,100 Pounds of Thrust in Gusty 26-mph Winds

Figures 6(a) and (b) show the combined effect of gusts, winds of 26 mph, and 2,100 pounds of rotor thrust on the spanwise blade bending moments. For the wind velocity of 26 mph, the rotor was trimmed by applying approximately 3° of cyclic pitch. The turbulence indicators show about the same disturbance to be present as in figure 5 (which presented the blade vibratory moments at zero thrust and, thus, zero rotor downwash). A comparison of the two figures, one without rotor downwash (fig. 5) and one with rotor downwash (fig. 6), both under similar atmospheric conditions, indicates that in figure 6 there is a large increase in vibratory blade bending moments. This increase is probably due to the normal calculable vibratory input (assuming uniform rotor downwash) plus the contribution of the unsymmetrical rotor downwash at this forward-flight speed.

If gusts were of primary importance, some indication of their effects should be apparent in the oscillograph traces of the blade bending moments. An examination of the record for 100 rotor revolutions taken at 2,100 pounds of rotor thrust in gusty winds of 26 mph showed that, regardless of variations in the turbulence-indicator traces, the bending-moment traces approximately repeat themselves for each rotor revolution.

Vibratory Bending Moments

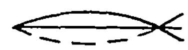
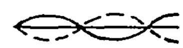
In figure 7, the total maximum amplitude, or the spread between the maximum and minimum values of the vibratory rotor-blade bending moments, in inch-pounds, is plotted against percent of blade radius for the three previously mentioned conditions. The lowest curve represents the blade at zero thrust in quiet air. The middle curve presumably shows the increase in vibratory moments due to gusts, and the top curve shows the amplitude for the combination of gusts with unsymmetrical rotor downwash. These curves clearly indicate that the effects of gusts on the blade bending moments are much smaller than the downwash effects. In general, the gust contribution is about 20 percent of the total vibratory moments experienced in winds averaging 26 mph at rated rotor thrust.

A comparison of these vibratory bending moments with the mean blade bending moments for the condition of 2,100 pounds of rotor thrust and gusty winds of 26 mph is shown in figure 8. The mean bending-moment values were taken from a harmonic analysis which is discussed subsequently. Here, blade bending moments are plotted against percent of blade radius. The dashed lines represent the total maximum positive and negative blade bending moments (vibratory plus mean values), and the mean or steady-state bending moment is identified by the solid line. All positive values in figure 8 indicate bending moments that contribute to compression in the top fibers of the blade, and all negative values indicate bending moments that contribute to tension in the top fibers. Essentially, the mean bending-moment curve takes a shape that would be expected when simplified rotor-blade bending theory is used. However, the amplitudes of the vibratory values are not accounted for by this theory. The curves show that for the rotor blade tested, the maximum positive moment at the 37-percent-radius station may be about 2.5 times as large as the mean bending moment at that station. The maximum negative moment, located at the 85-percent-radius station, is about 2.3 times the value of the corresponding mean bending moment. As previously discussed, these high vibratory bending moments in gusty winds of 26 mph are attributed primarily to the unsymmetrical rotor downwash.

Harmonic Analysis

The frequency at which vibratory moments occur in the rotor blade is very important in the design, especially in an analysis of the fatigue life of the structure. In order to determine the predominant harmonics and to compare those harmonics with the blade natural frequencies, a 48-point harmonic analysis was made of a typical cycle of the bending-moment traces.

The results of this analysis are presented in figures 9 and 10. Figure 9 shows the harmonic content of the blade bending-moment traces at 7 spanwise stations in very quiet air (approximately zero wind velocity) at 0 and 2,100 pounds of rotor thrust. Two types of bars are shown at each station. The solid bars represent the harmonic amplitudes excited at zero rotor thrust and, therefore, with no inflow through the rotor disk. The open bars indicate the harmonic amplitudes produced at 2,100 pounds of rotor thrust. The bar on the extreme left at each station represents the mean or steady-state bending moment and is labeled positive or negative according to the moment at the particular station. The rotor speed for all data presented was approximately 4 rps. The experimental frequency of the blade in cycles per second for each harmonic can be obtained by multiplying the harmonic number by 4; that is, the seventh harmonic would correspond to 28 cps at a rotor angular velocity of 4 rps. The calculated natural frequencies of the blade are shown in the following table:

Bending mode	Frequency, cps	Sketch (a)
First	9.6	
Second	16.8	
Third	26.8	

[a]The horizontal line in each sketch is the line of zero deflection.

At a rotor angular velocity of 4 rps, the first bending natural frequency falls between the second and third harmonics, the second bending natural frequency falls near the fourth harmonic, and the third bending natural frequency falls near the seventh harmonic.

Figure 10 presents the harmonic content of the blade bending moments at 6 spanwise stations for a rotor operating in gusty air with an average wind velocity of 26 mph at 0 rotor thrust (no rotor downwash) and 2,100 pounds of rotor thrust.

The effects of gusts on the various harmonics can be seen by comparing the solid bars of figure 9 with the solid bars of figure 10. Since the rotor is operating at zero thrust (zero blade angle of attack), there are no inflow effects and the increase in amplitude of the harmonics apparently stems from gust influences. In general, the gust contribution appears to have a total vibratory amplitude of about 450 inch-pounds over most of the blade radius (fig. 7). Specifically, at the 37-percent-radius station, the total vibratory amplitude of the gust is approximately 530 inch-pounds, which is 52 percent of the steady-state bending moment obtained with 2,100 pounds of rotor thrust in approximately zero wind velocity. The open bars of figure 10 illustrate the combined effects of gusts and rotor downwash on the blade harmonics. This figure clearly shows the predominance of those harmonics which are close to the natural bending frequencies of the blade, namely: the second and third harmonics, which are close to the frequency of the first bending mode, the fourth harmonic, which is close to the frequency of the second bending mode, and the seventh harmonic, which is close to the frequency of the third bending mode.

The harmonic content of the rotor blades under similar gust conditions at zero thrust and at 2,100 pounds of thrust indicates (at 26 mph) the rather secondary effect which the gusts may produce as compared with the vibrations which arise from operation of the rotor at 2,100 pounds of thrust and this forward speed.

Effect of Tip Weights

A means of altering the blade vibratory moments would be the addition of weights to the rotor-blade tips. A reduction in total stress might or might not be obtained, depending on the individual case. However, it is of interest to determine the effect of weights on the rotor-blade bending moment, inasmuch as helicopters with weights (in the form of jet engines) attached to the blade tips are now being used. The mean blade bending moment is plotted against percent of blade radius in figure 11 for various tip weights at a rotor thrust of 2,100 pounds, an average wind velocity of 8 mph, and a rotor angular velocity of 4 rps. As would be expected, increasing the tip weight reduces the bending moment over the inboard part of the blade and increases the moment near the tip. It appears that the addition of tip weights is an effective means of controlling within limits the mean moment distribution along the span of the blade.

The effect of the tip weights on the vibratory amplitude of the bending moments is shown in figure 12 as a plot of maximum vibratory amplitude against percent of blade radius for 0-and 7-pound tip weight. The maximum vibratory amplitude is reduced about 20 percent over most of the blade span by the addition of the 7-pound tip weight.

CONCLUDING REMARKS

On the basis of the tests of a rotor on the Langley helicopter test tower in calm and gusty air, the following concluding remarks regarding blade bending moments can be made:

1. The effect of gusts on rotor-blade bending moments appears to be secondary compared with the vibratory moments obtained with 2,100 pounds of rotor thrust for the 26-mph wind velocity tested and analyzed.

2. The predominant vibratory moments occur at frequencies corresponding to the blade natural frequencies in the first, second, and third flapwise bending modes.

3. Tip weights can be used to control the blade bending-moment distribution and to decrease the vibratory blade bending moments.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., December 14, 1953.

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2. Carpenter, Paul J.: Effect of Wind Velocity on Performance of Helicopter Rotors As Investigated With the Langley Helicopter Apparatus. NACA TN 1698, 1948.

3. Tolefson, H. B., Pratt, K. G., and Thompson, J. K.: An Experimental Study of the Relation Between Airplane and Wind-Vane Measurements of Atmospheric Turbulence. NACA RM L52L29b, 1953.

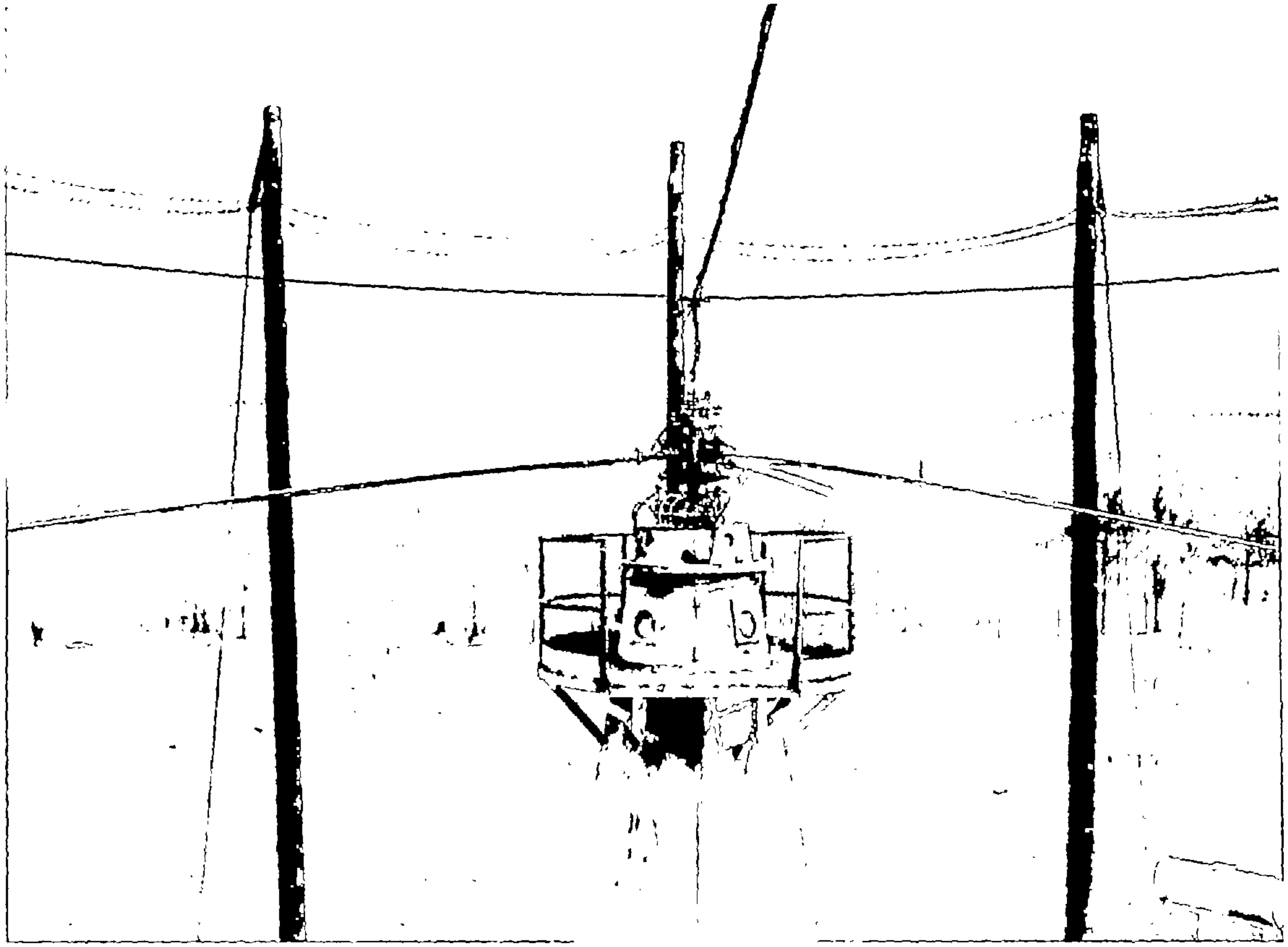

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Figure 1.- Rotor installation on Langley helicopter test tower.

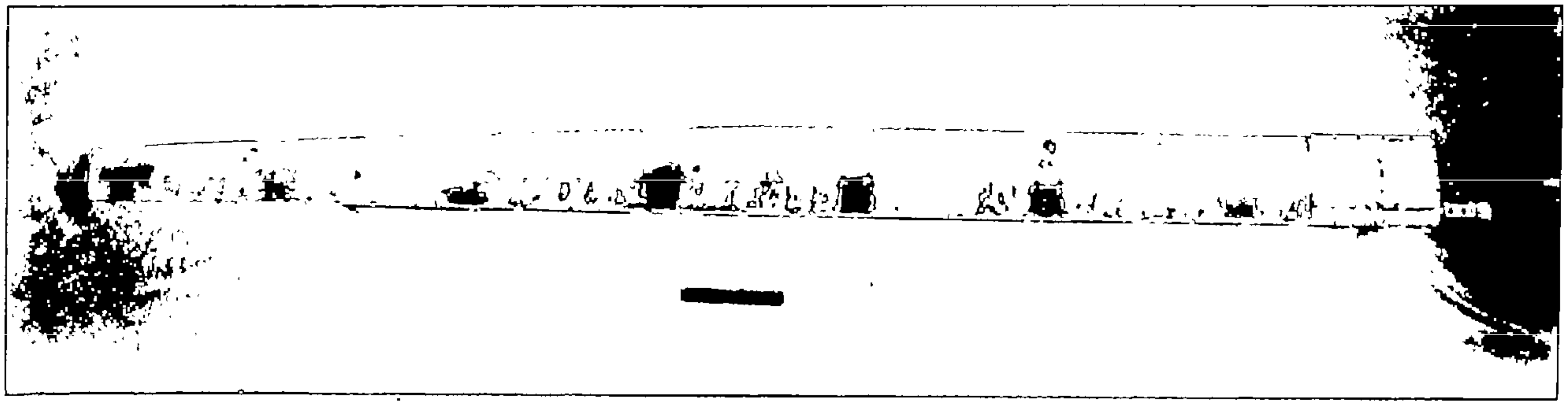

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Figure 2.- Test blade with 7-pound tip weight.

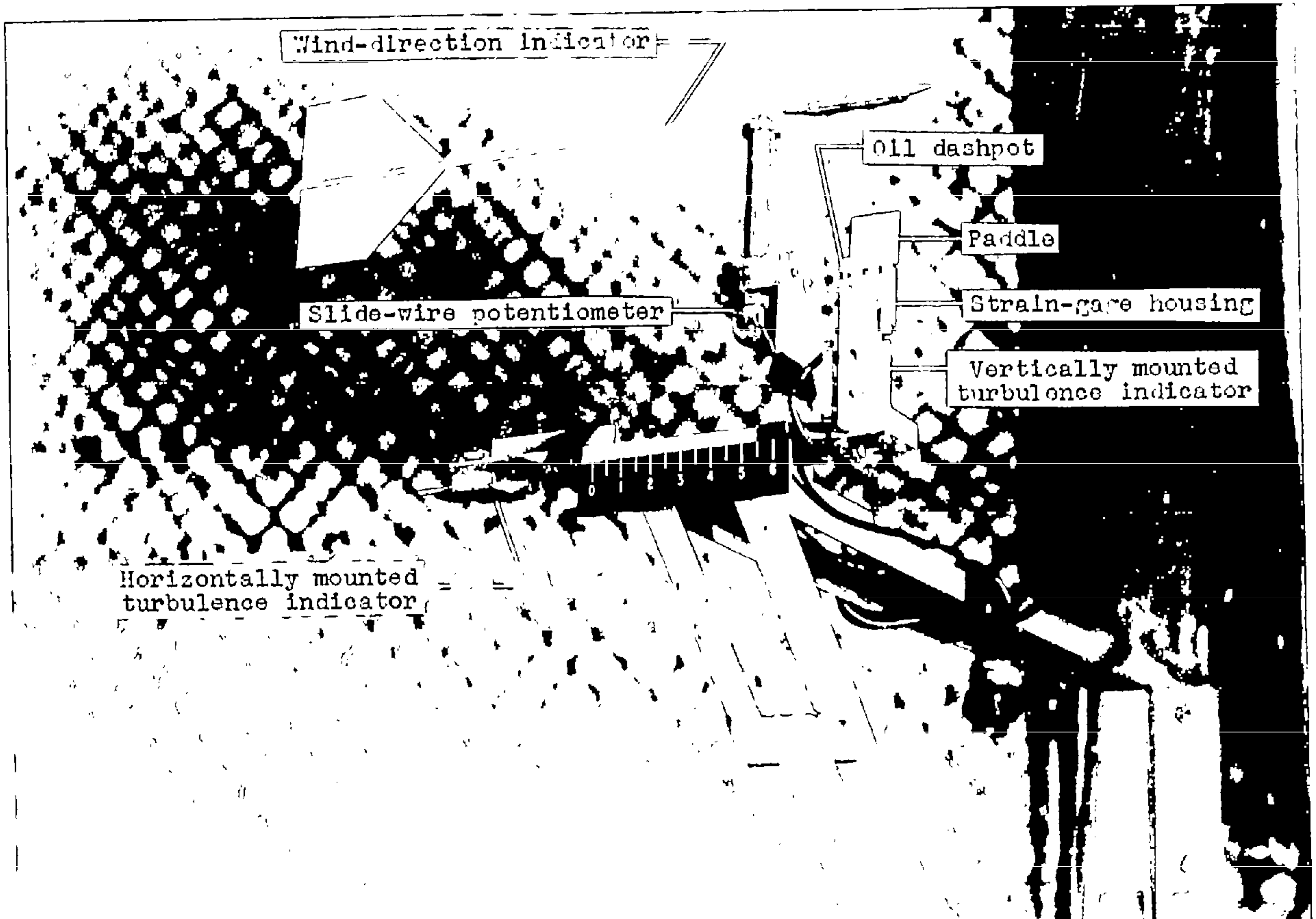

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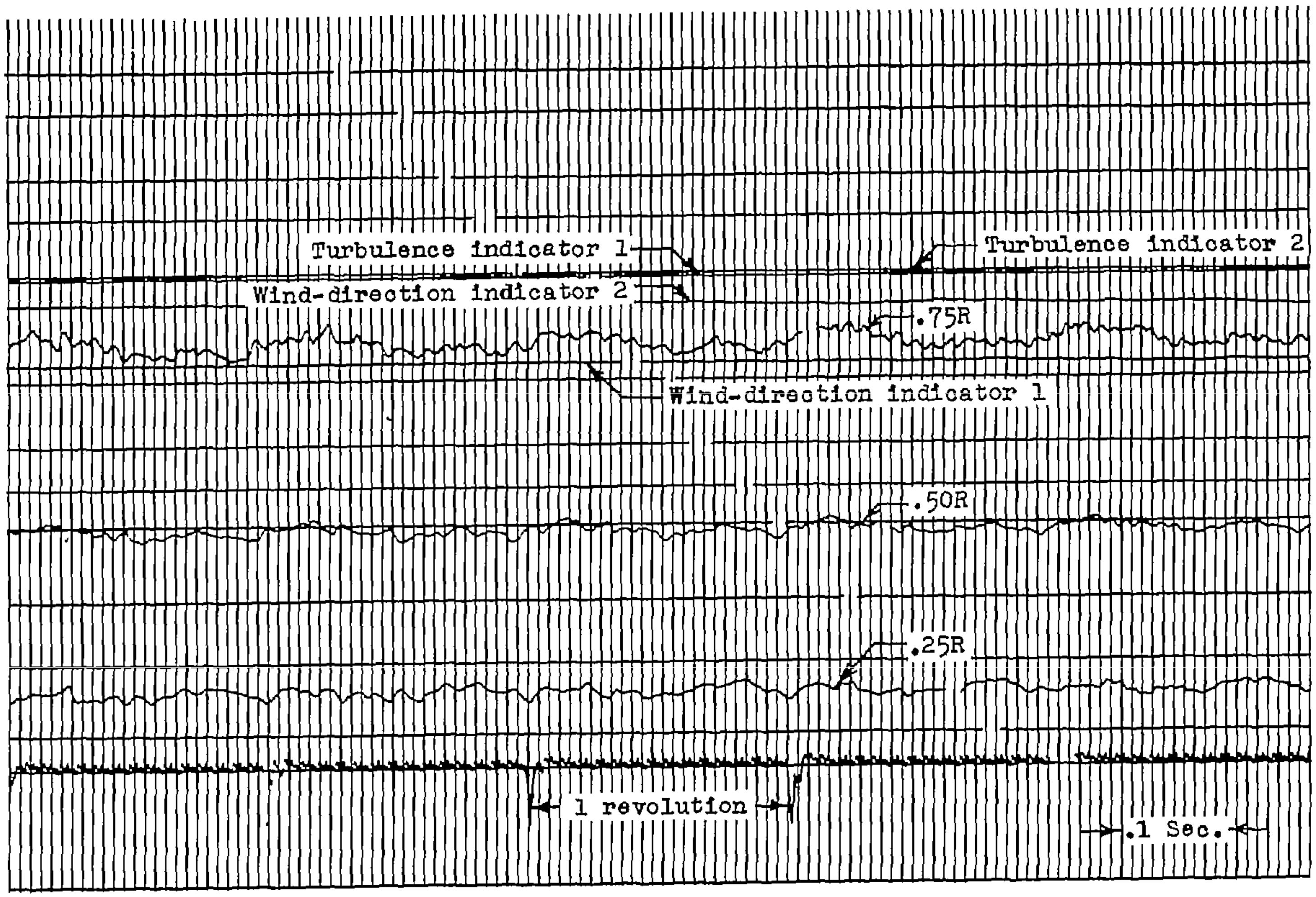
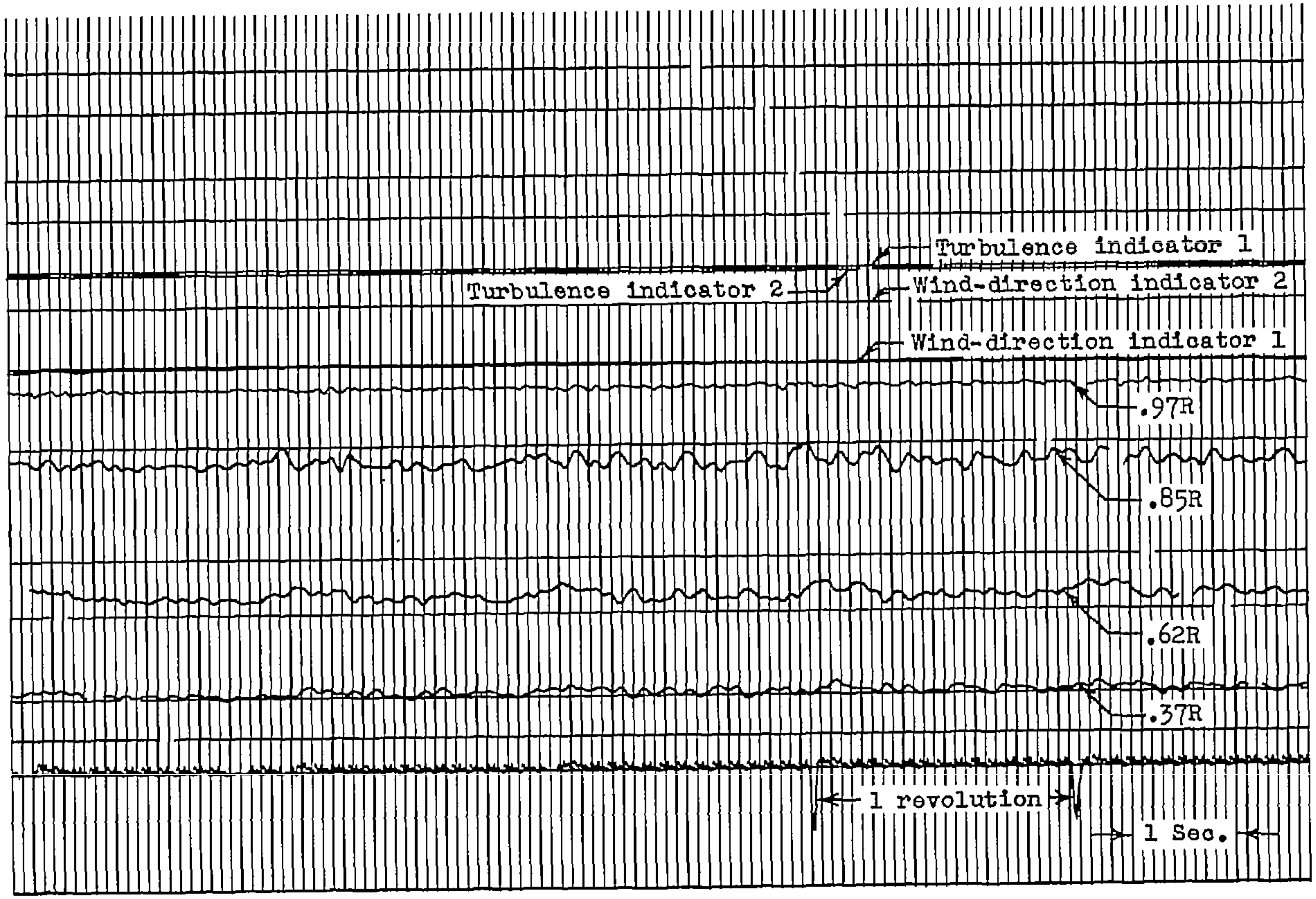
Figure 3.- Gust and wind-direction indicating system.



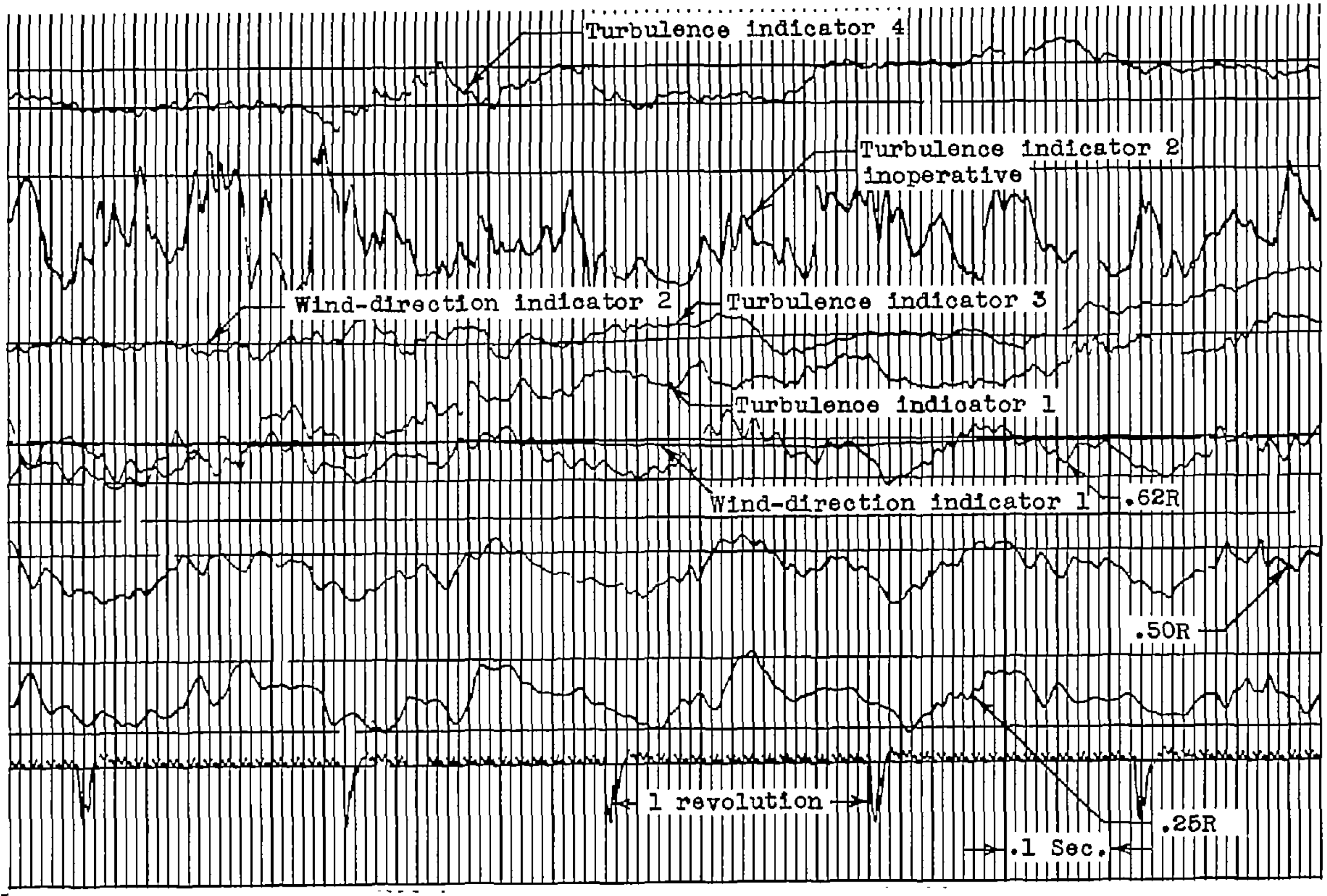
(a) 25, 50, and 75 percent of blade radius.

Figure 4.- Oscillograph record of gusts, wind direction, and bending moments for winds of approximately zero velocity, rotor angular velocity of about 240 rpm, and rotor thrust of zero.



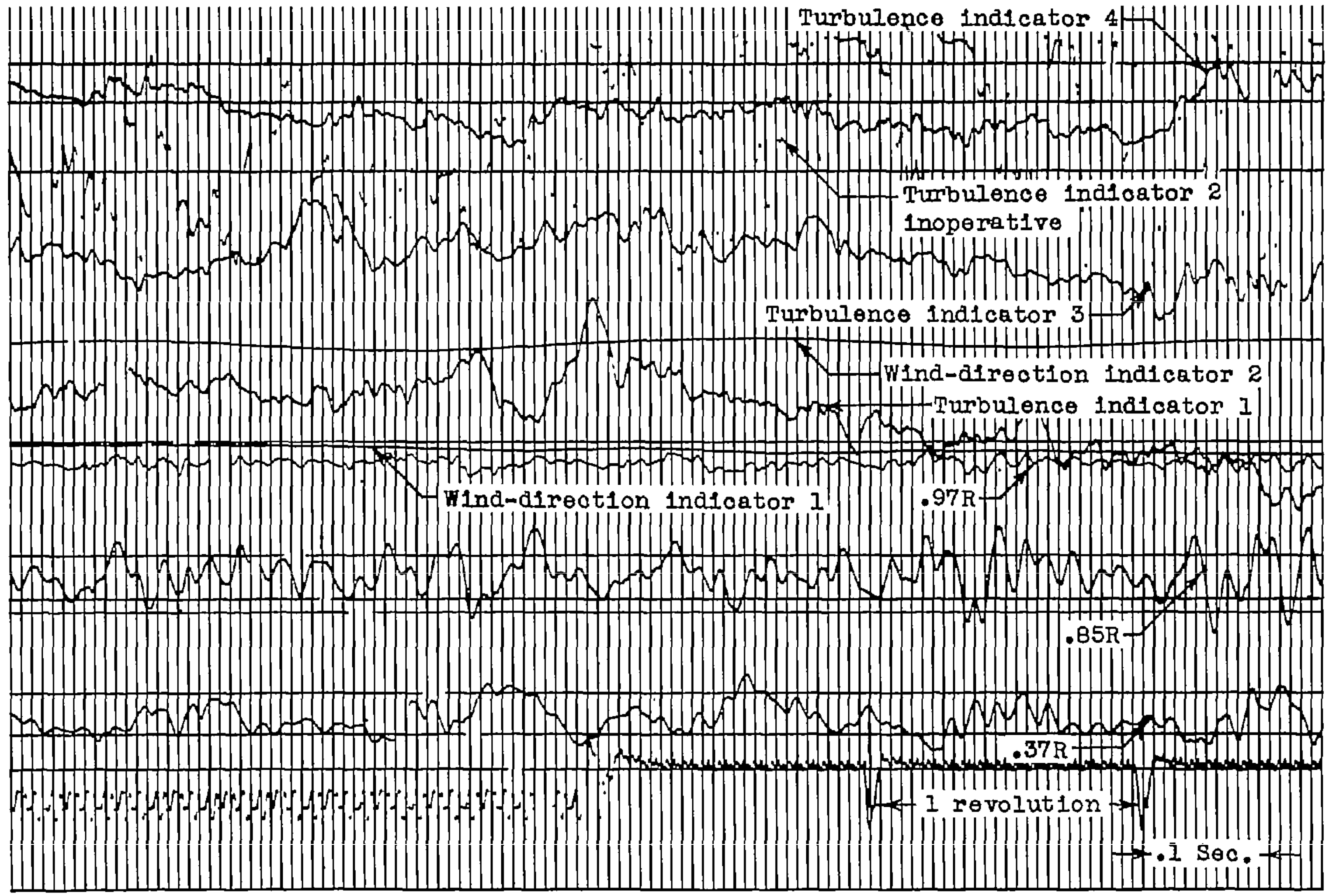
(b) 37, 62, 85, and 97 percent of blade radius.

Figure 4.- Concluded.



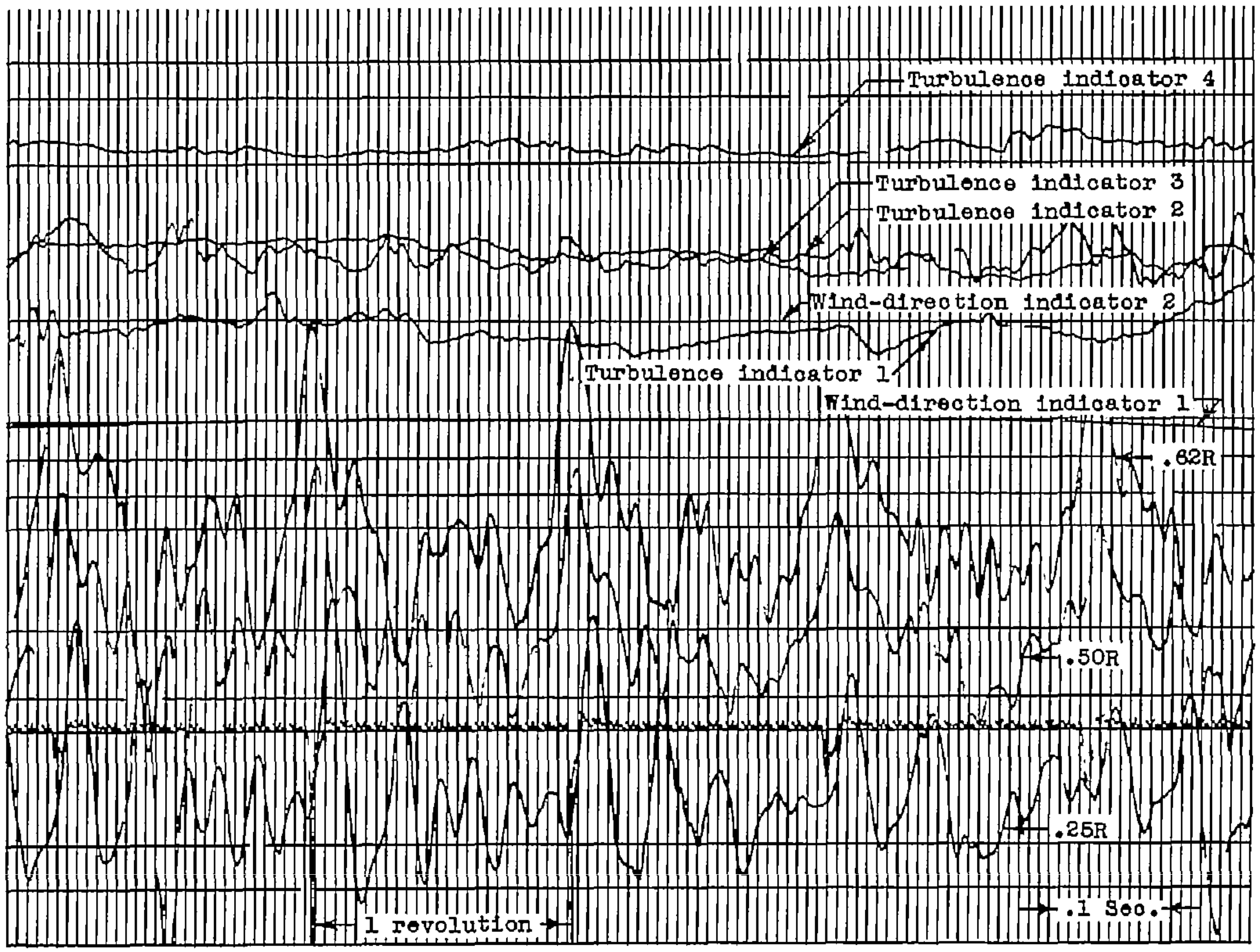
(a) 25, 50, and 62 percent of blade radius.

Figure 5.- Oscillograph record of gusts, wind direction, and bending moments for winds of 26 mph, rotor angular velocity of about 240 rpm, and rotor thrust of zero.



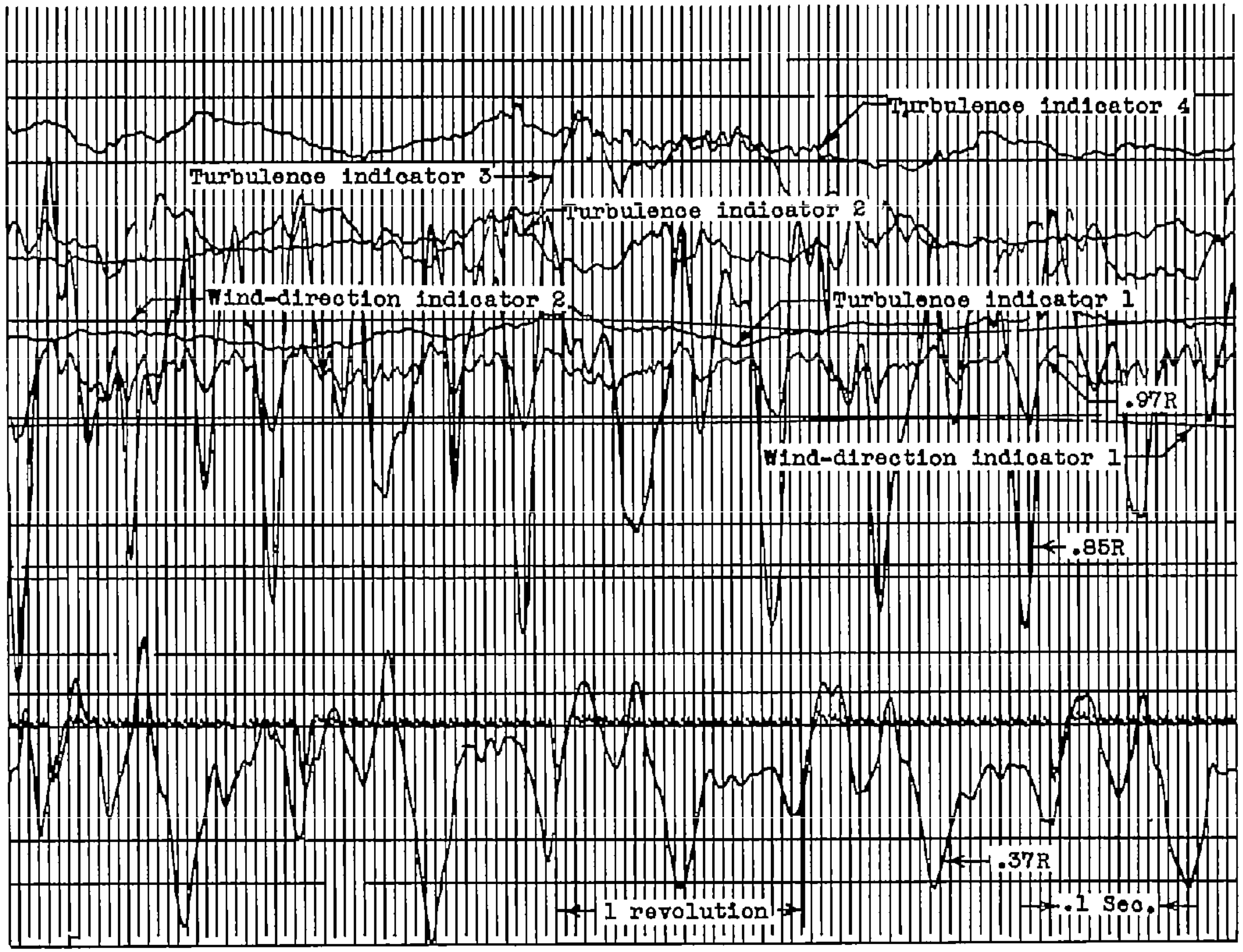
(b) 37, 85, and 97 percent of blade radius.

Figure 5.- Concluded.



(a) 25, 50, and 62 percent of blade radius.

Figure 6.- Oscillograph record of gusts, wind direction, and bending moments for winds of 26 mph, rotor angular velocity of about 240 rpm, and rotor thrust of 2,100 pounds.



(b) 37, 85, and 97 percent of blade radius.

Figure 6.- Concluded.

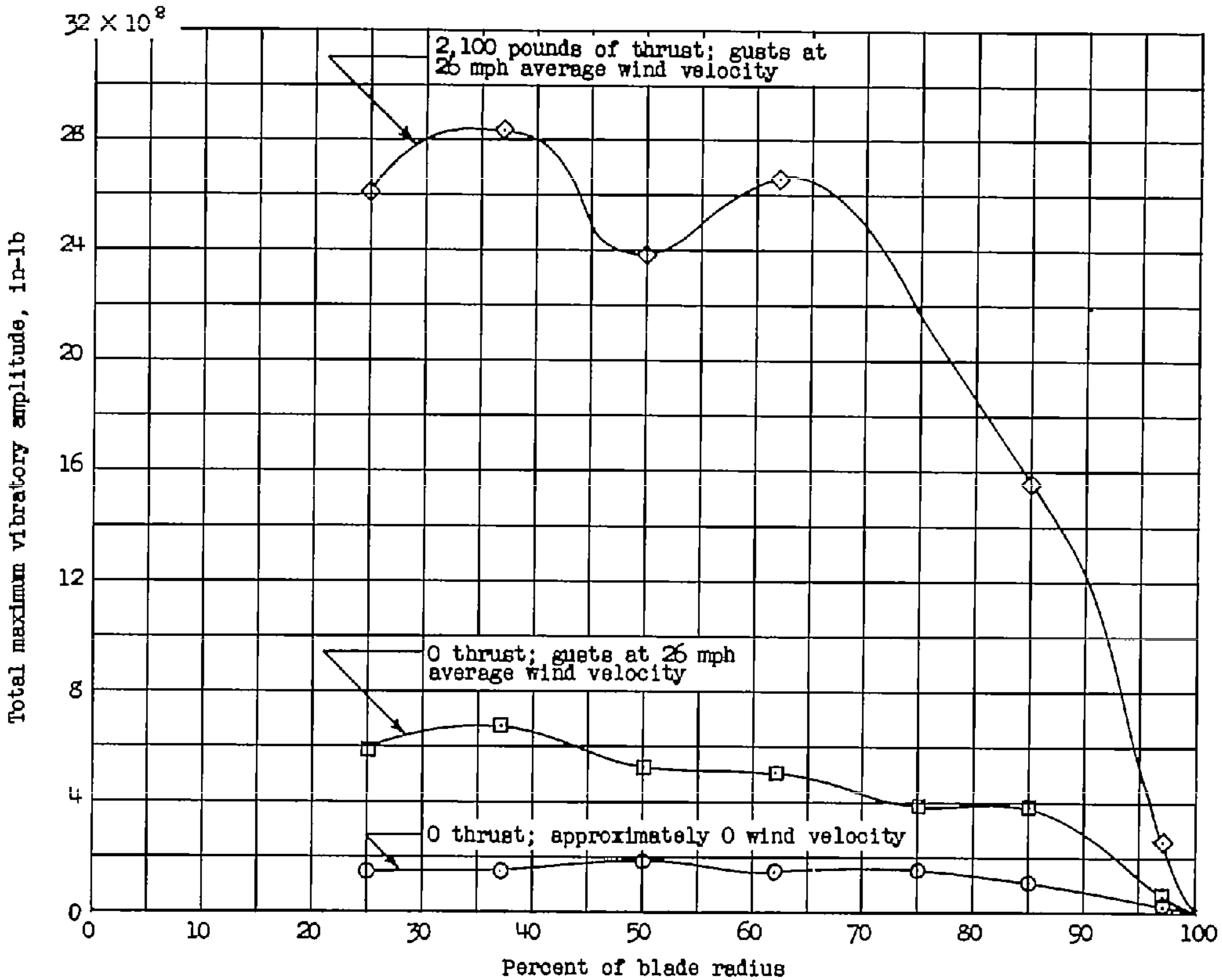


Figure 7.- Comparison of gust and rotor-downwash effects on the total maximum vibratory amplitude of rotor-blade bending moments at a rotor angular velocity of about 240 rpm.

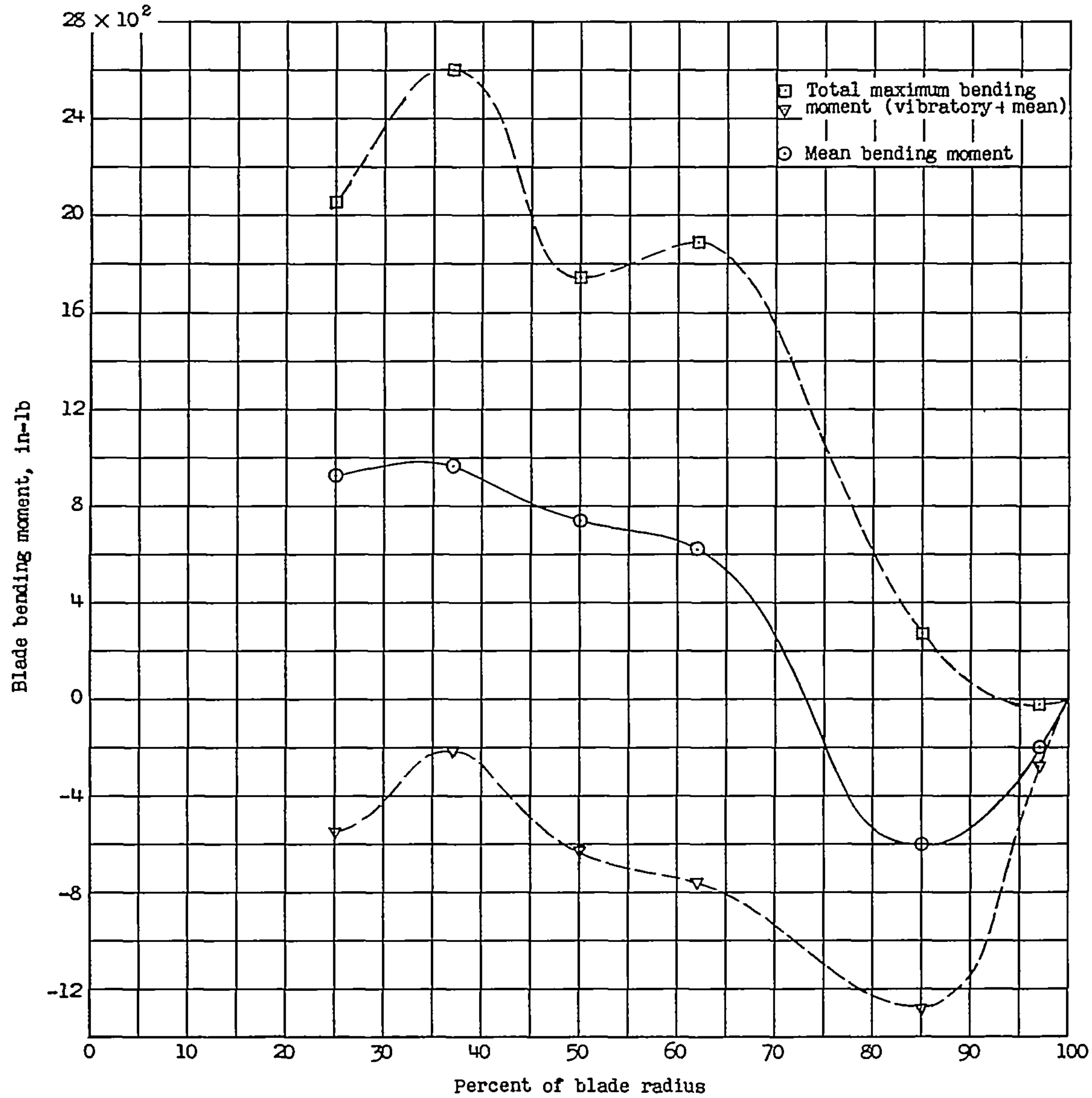


Figure 8.- Mean and vibratory amplitude of blade bending moments for rotor thrust of 2,100 pounds, rotor angular velocity of about 240 rpm, and winds of 26 mph.

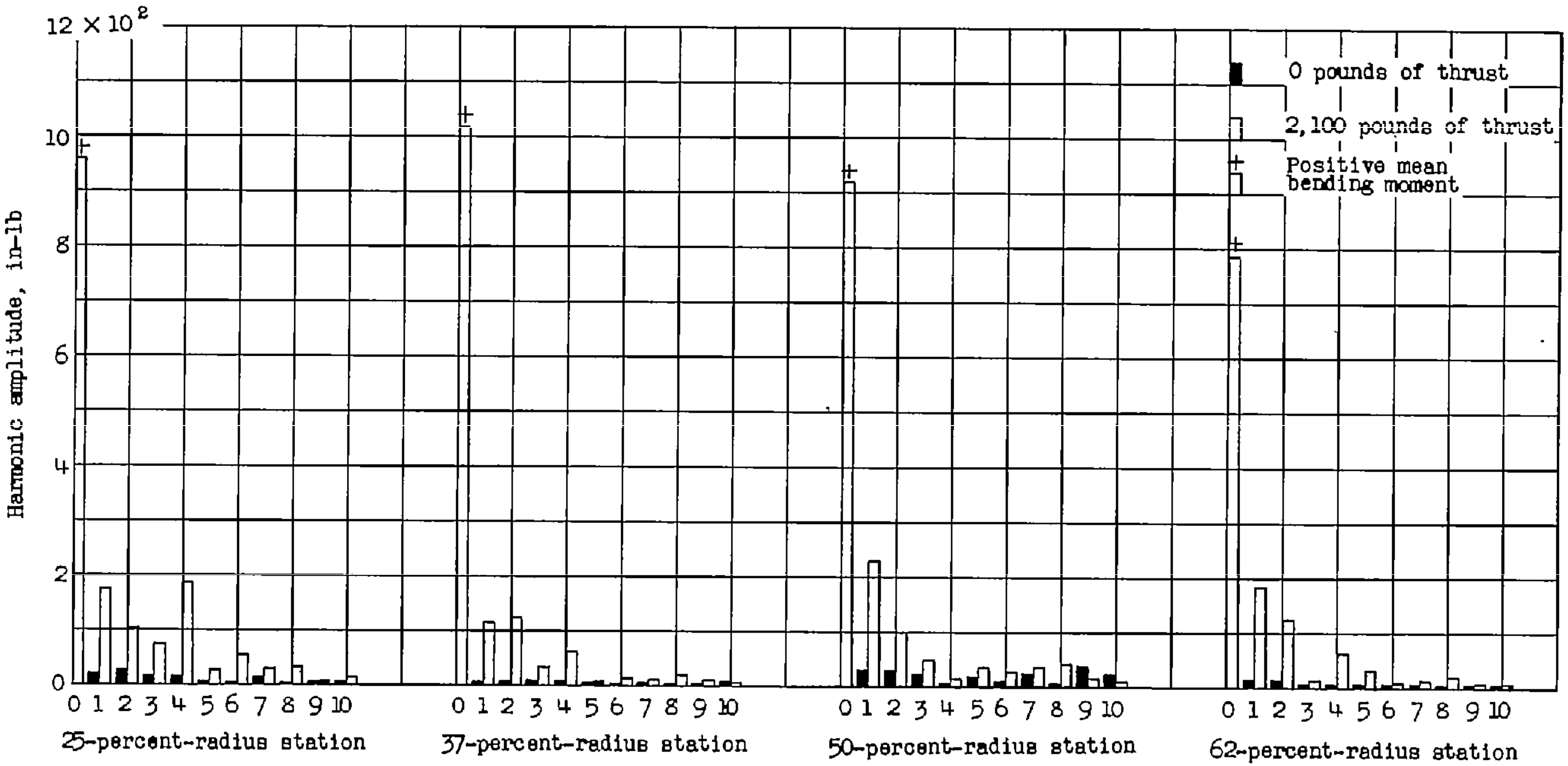


Figure 9.- Amplitude of first 10 harmonics of blade bending moment at 7 spanwise stations for rotor thrust of 0 and 2,100 pounds, rotor angular velocity of about 240 rpm, and winds of approximately zero velocity.

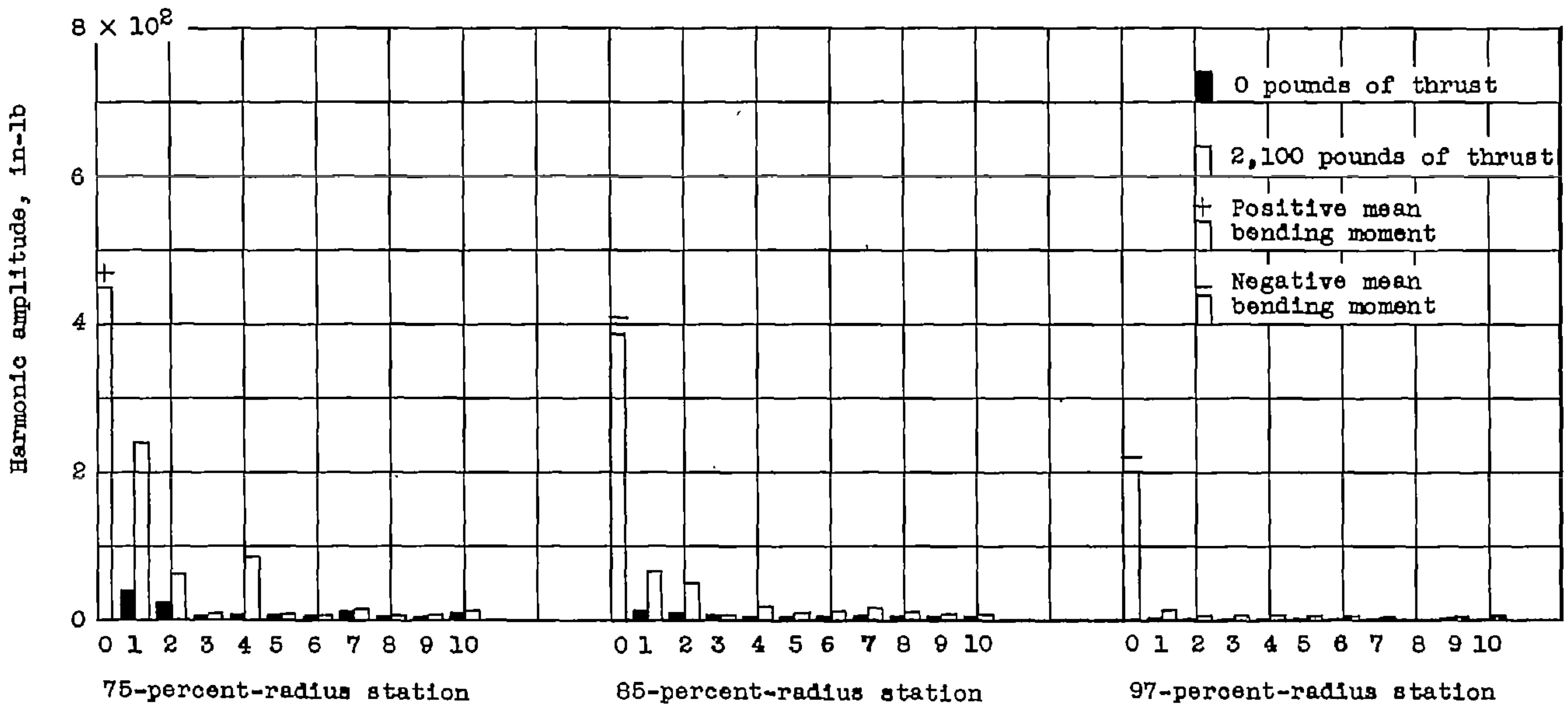


Figure 9.- Concluded.

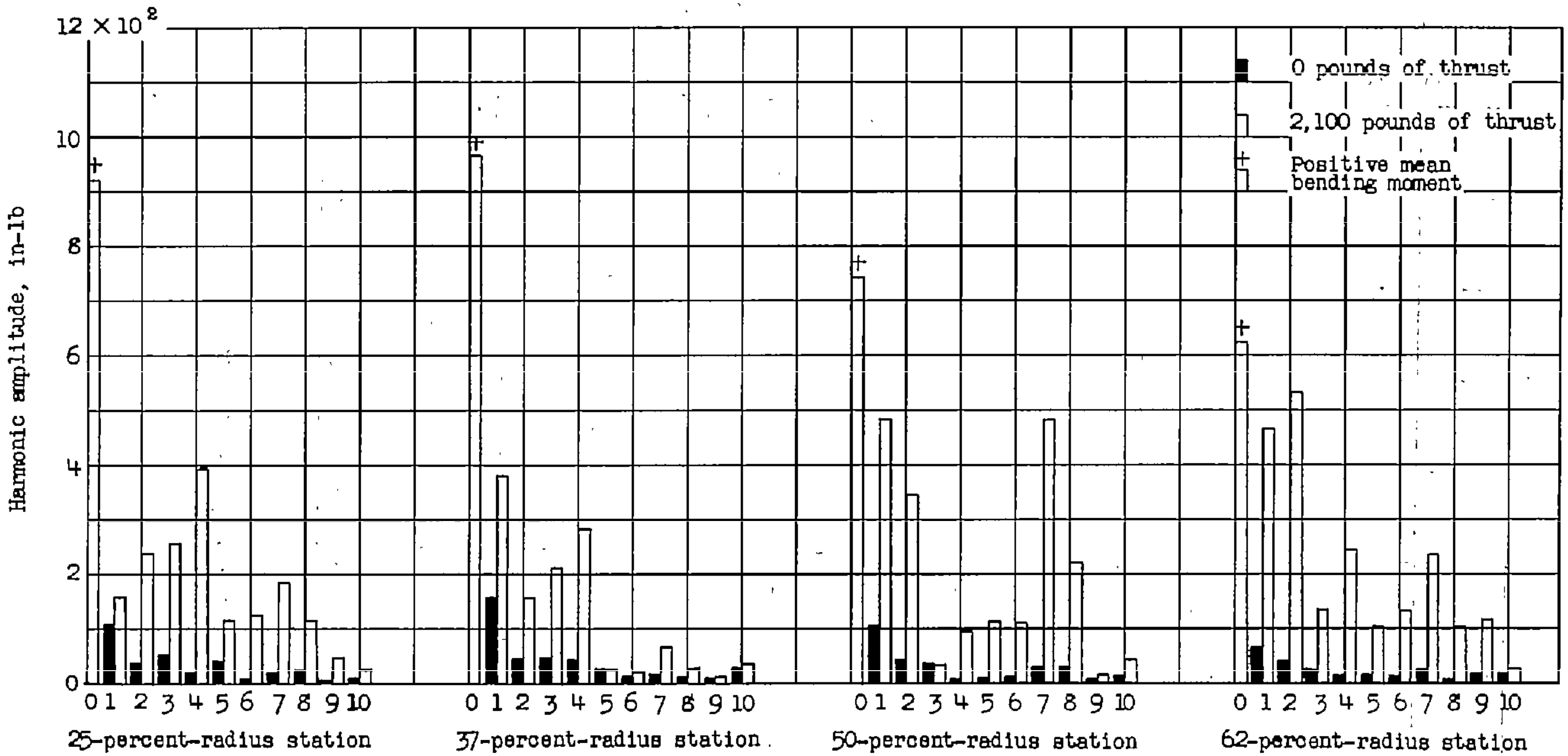


Figure 10.- Amplitude of first 10 harmonics of blade bending moment at 6 spanwise stations for rotor thrust of 0 and 2,100 pounds, rotor angular velocity of about 240 rpm, and winds of 26 mph.

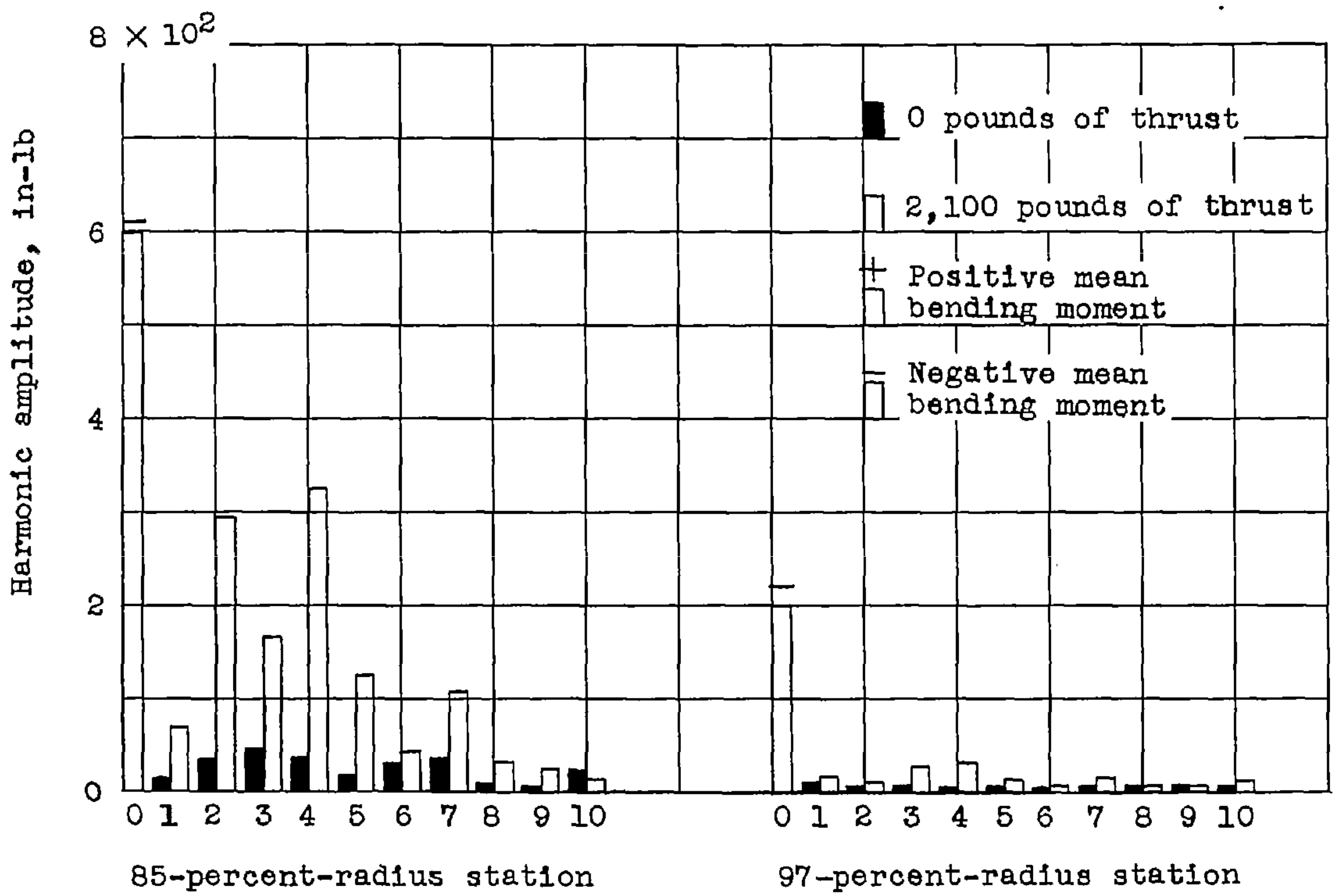


Figure 10.- Concluded.

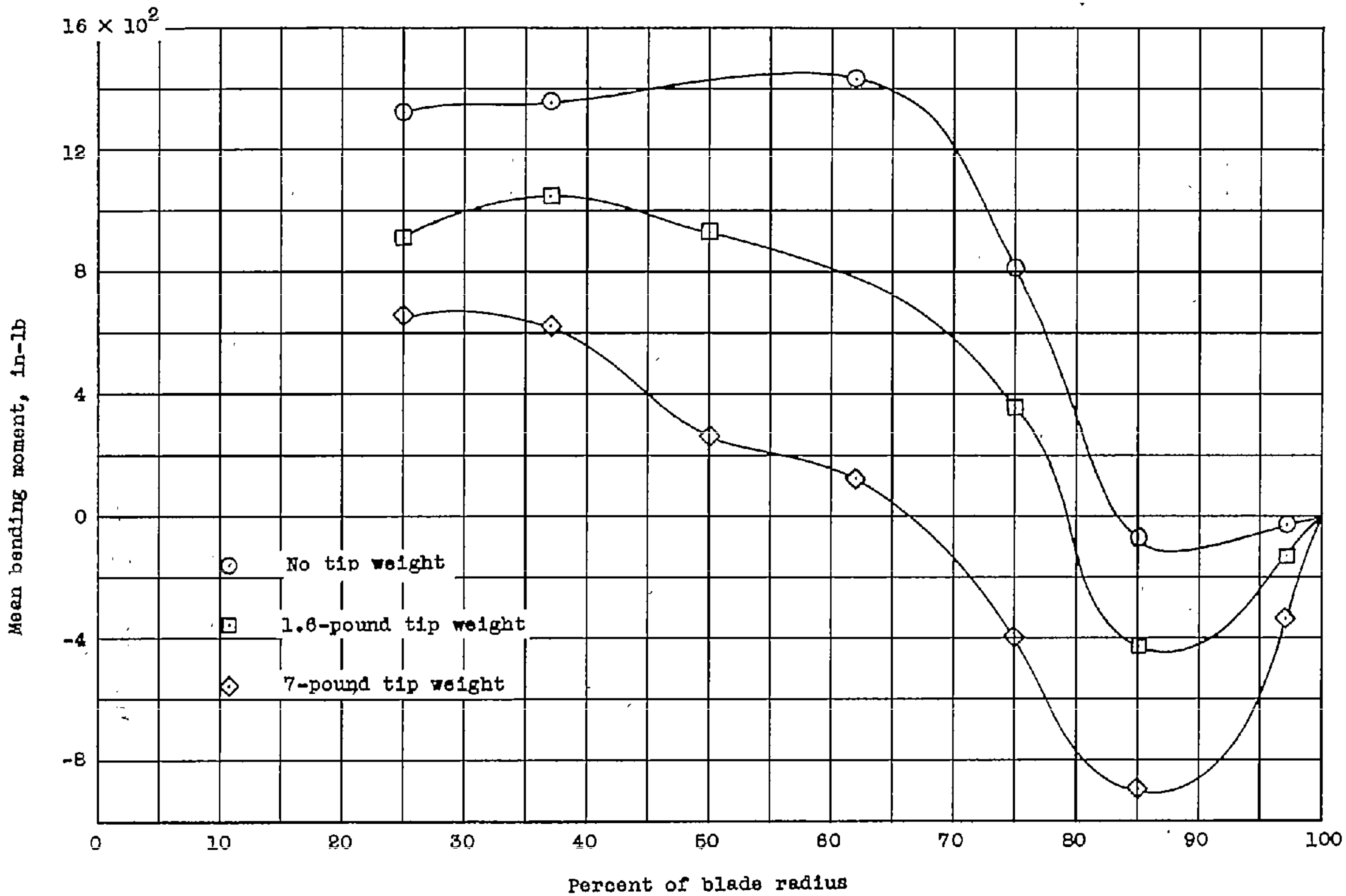


Figure 11.- Variation of blade mean bending moment with tip weight for rotor thrust of 2,100 pounds, rotor angular velocity of about 240 rpm, and winds of 8 mph.

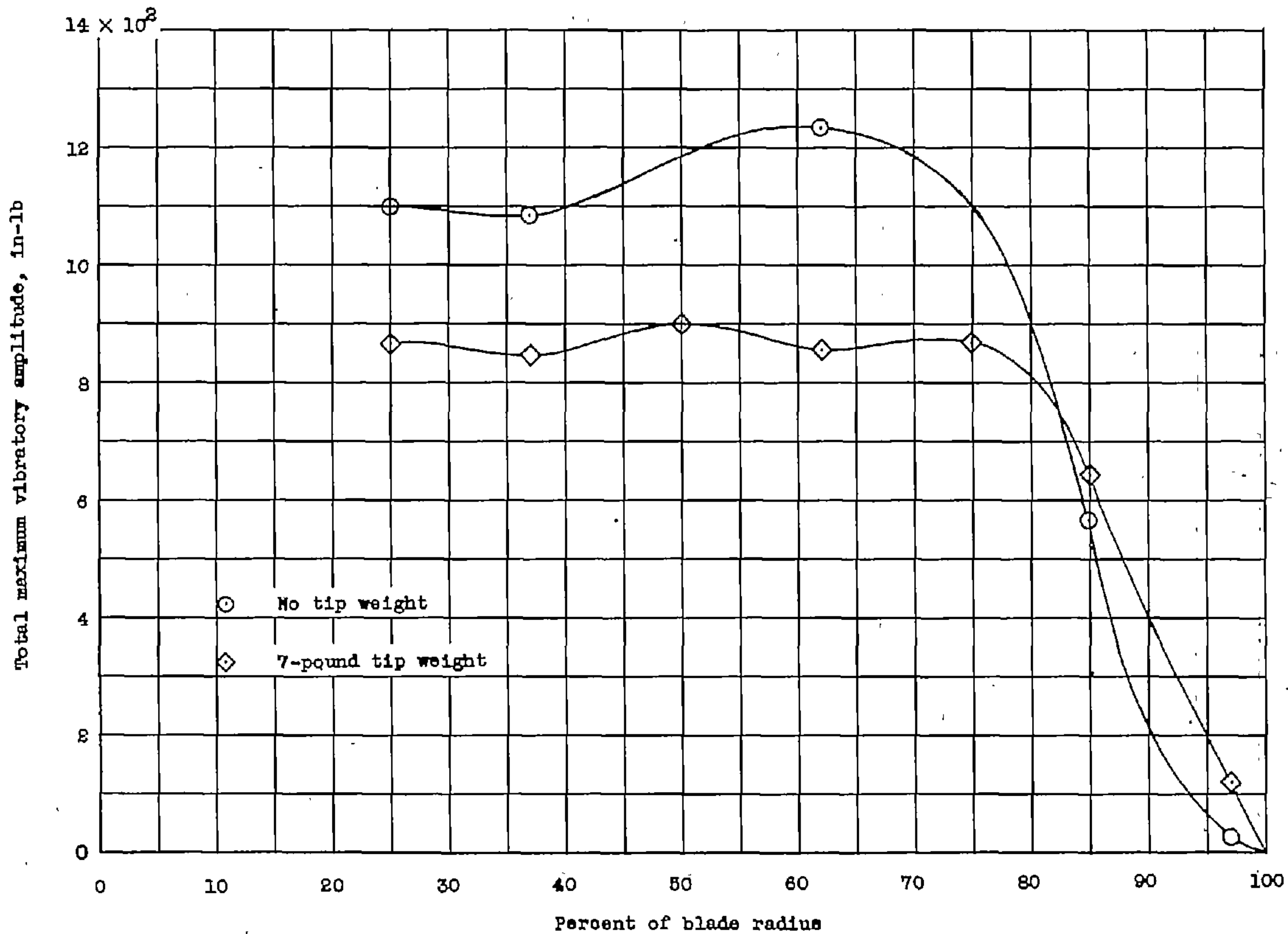


Figure 12.- Comparison of total amplitudes of blade vibratory bending moments for tip weights of 0 and 7 pounds, rotor thrust of 2,100 pounds, winds of 8 mph, and rotor angular velocity of about 240 rpm.

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